Project ESD12010:
Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits

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U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
August 13-16, 2018

Presentation Outline

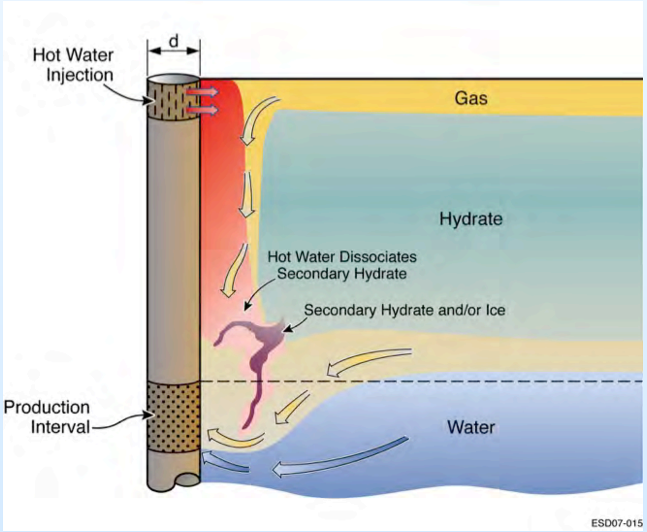
1. Accomplishments to Date (overview)
2. Technical Status (FY18/current BP)
    - Code Maintenance and Upgrades
    - Assessment of Resource Recovery During Production from Oceanic Hydrates
    - Support of DOE Field Activities and Collaborations
        - IGHCCS2
        - **Simulation of NGHP-02-9 Offshore India Production Test**
3. Accomplishments to Date (pre-FY18)
4. Paths Forward
5. Lesson Learned
6. Synergies

Accomplishments to Date

Objective: **To develop the knowledge base and quantitative predictive capability to describe the most important processes and phenomena associated with gas production from hydrate deposits**

Program Components:

- **TOUGH+HYDRATE: simulator for hydrate-bearing reservoirs**
- **Design and evaluation of DOE and industry production tests**
- **Behavior of hydrates in the natural environment**
- **Coordinating laboratory work**
- **Collaborations and training**



This is the 6th year (budget period) of the current project, part of a 20-year DOE-funded hydrate program at LBNL

Technical Status

1. Code Maintenance and Upgrades

2. Assessment of Resource Recovery During Production from Oceanic Hydrates

3. Support of DOE Field Activities and Collaborations
    1. IGHCCS2
    2. **Simulation of NGHP-02-9 Offshore India Production Test**

Code Maintenance and Upgrades

TOUGH+HYDRATE Codes

1. Components

(1) H_2O
(2) CH_4
(3) Hydrate (*)
(4) Salt
(5) Inhibitor
(6) Heat

Components in red: Minimum necessary
(*): For kinetic dissociation

30 Possible phase combinations

2. Phases

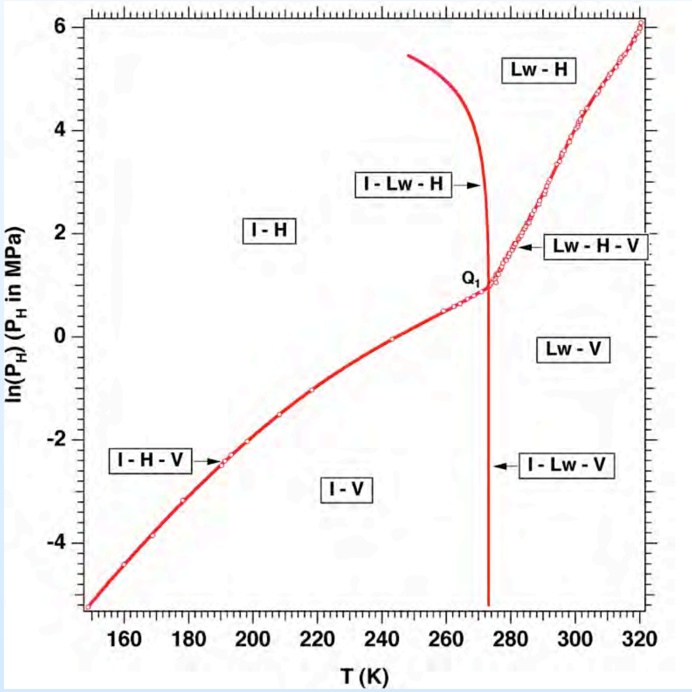
(1) Aqueous
H_2O, CH_4, S, I

(2) Gas
CH_4, H_2O, I

(3) Solid-Hydrate
$CH_4.N_mH_20$

(4) Solid-Ice
H_2O

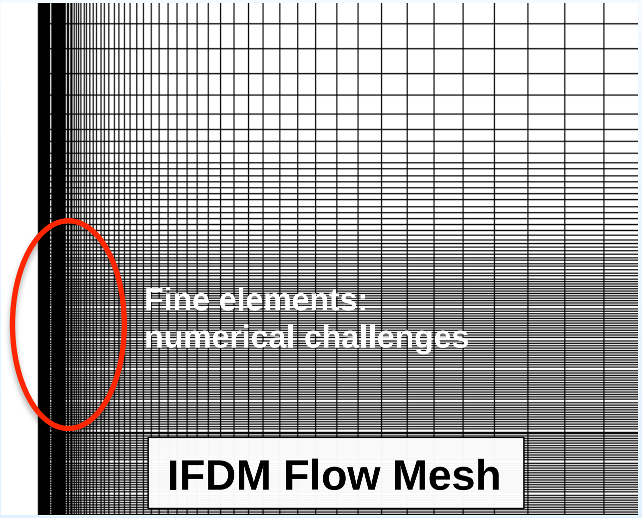
Latest hydration *P-T* relationships; state-of-the art

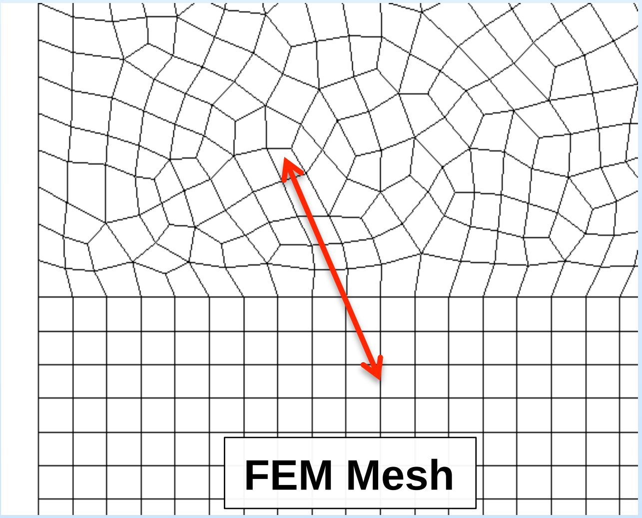


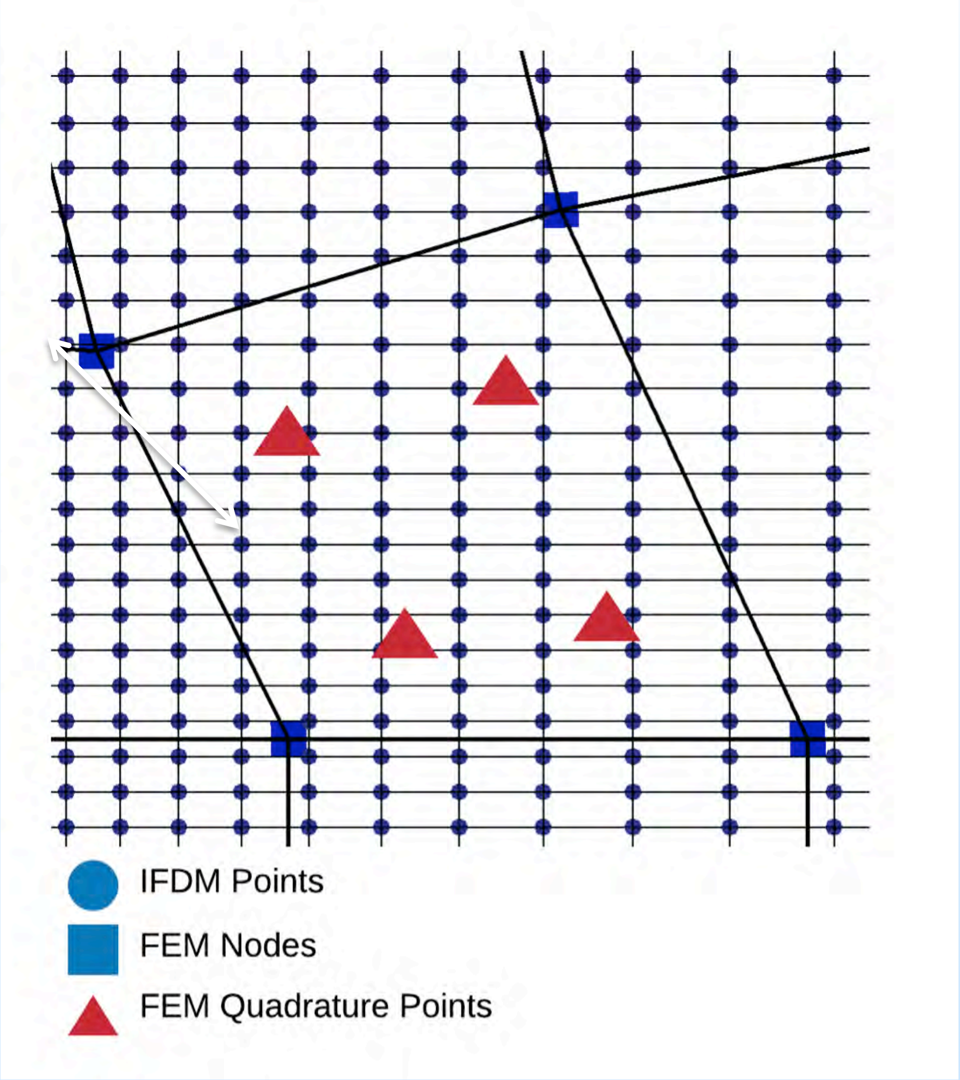
T+H is a fully compositional simulator capable of handling (a) equilibrium or kinetic dissociation, and (b) all possible dissociation mechanisms (depressurization, thermal stimulation, inhibitor effects, combinations)

Code Maintenance and Upgrades

New “Millstone” Coupled Geomechanical Simulator







Code Maintenance and Upgrades

- **Millstone includes a 2D axisymmetric formulation for vertical well problems**
- **Pure-C code with Python-based interface**
- **User-controlled constitutive models**
- **New coupled T-H-M codebase released in January 2018:**

Moridis, G.J., Reagan, M.T., Queiruga, A.F., “The TOUGH+Millstone Code for the Analysis of Coupled Flow, Thermal, Chemical, and Geomechanical Processes in Hydrate-Bearing Geologic Media, Part I: The Hydrate Simulator,” submitted to *Transport in Porous Media*.

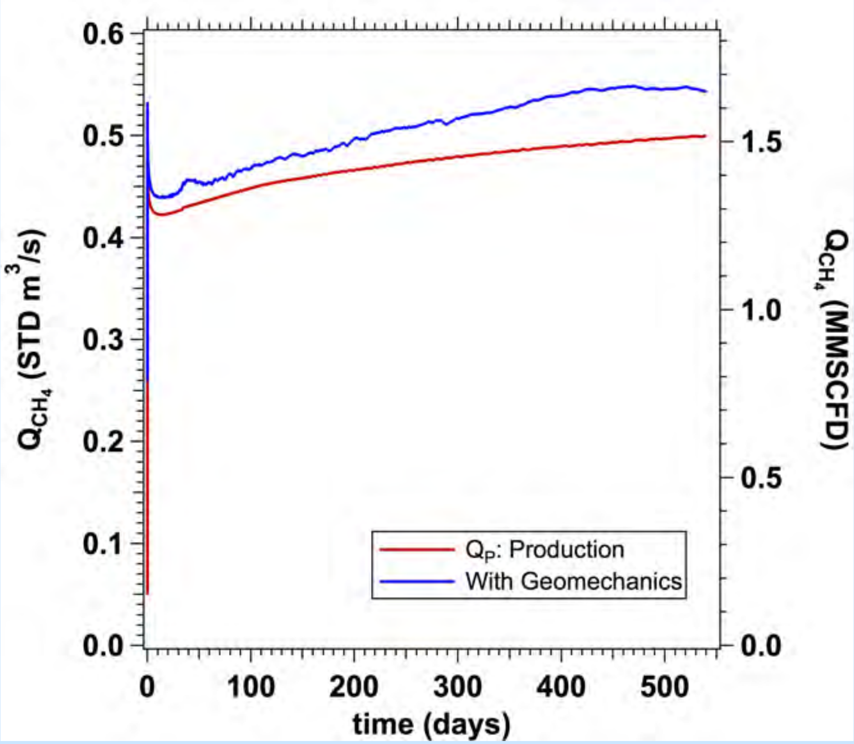
Queiruga, A.F., Moridis, G.J., Reagan, M.T., “The TOUGH+Millstone Code for the Analysis of Coupled Flow, Thermal, Chemical, and Geomechanical Processes in Hydrate-Bearing Geologic Media, Part II: Numerical Algorithms and the Stone Geomechanical Simulator,” submitted to *Transport in Porous Media*.

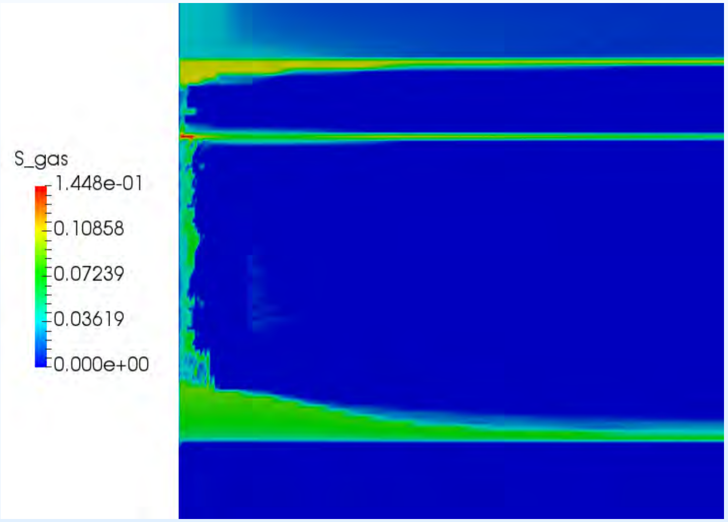
Reagan, M.T., Queiruga, A.F., Moridis, G.J., “The TOUGH+Millstone Code for the Analysis of Coupled Flow, Thermal, Chemical, and Geomechanical Processes in Hydrate-Bearing Geologic Media, Part III: Application to Production Simulation,” submitted to *Transport in Porous Media*.

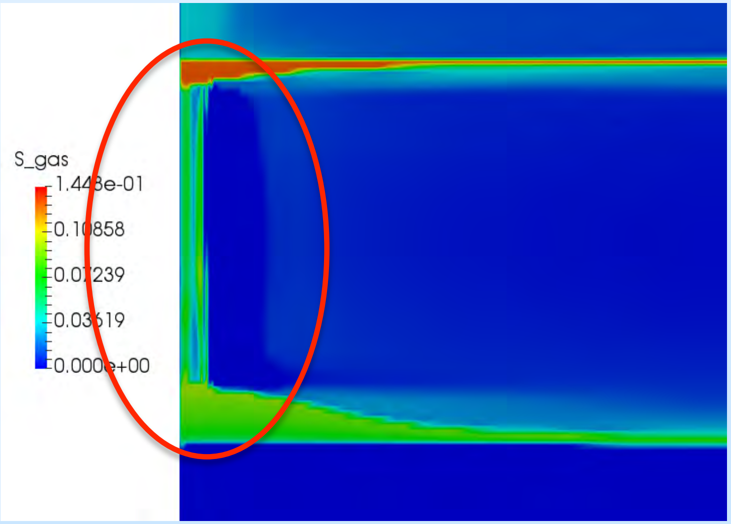
Assessment of Resource Recovery During Production from Oceanic Hydrates

Importance of Coupled Geomechanics

- Addition of coupled geomechanics increases predicted dissociation/production rate
- Changes evolution of system → heterogeneous dissociation vs. lensing







International GH Code Comparison Study

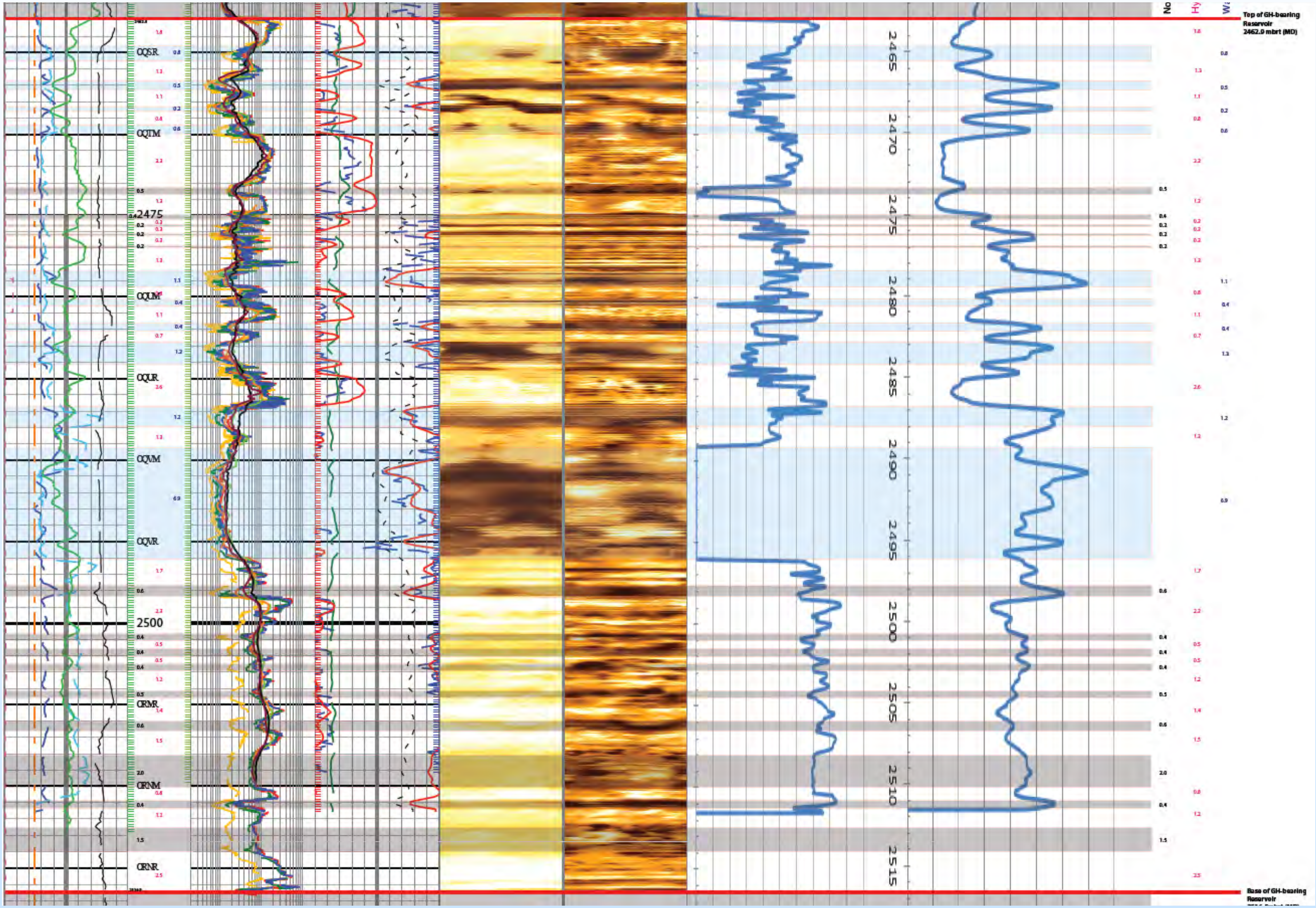
International effort to compare coupled flow-thermal-geomechanical simulators used for the simulation of gas hydrate production

- Shared test problems ranging from 1D flow simulations to 3D T-H-M production cases
- LBNL problem lead for Problem #3 (radially symmetric flow and geomechanics, compared to **analytical solution**)

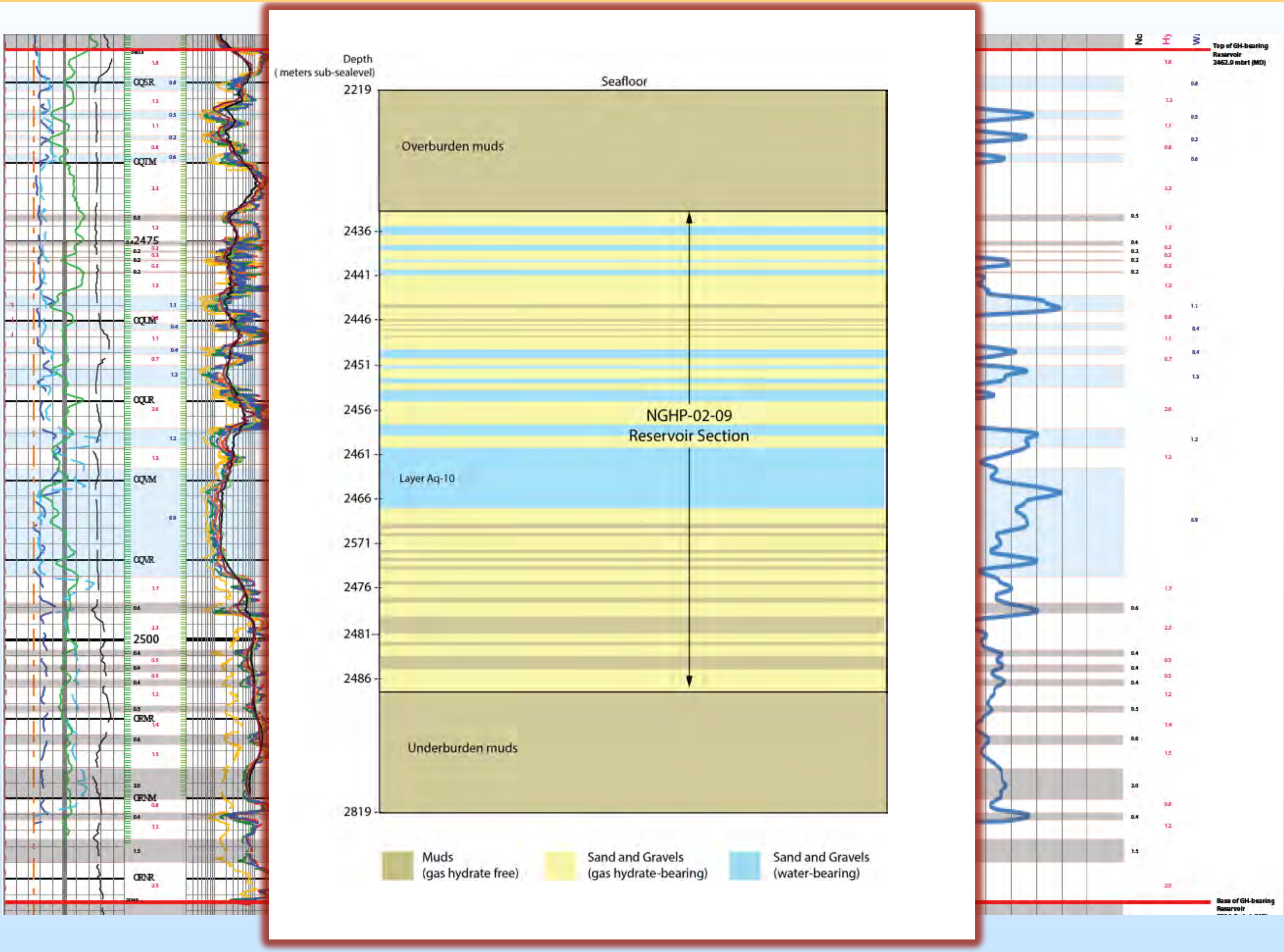
- LBNL also testing **mesh convergence** for standard Darcy-based hydrate simulation methods
  - **How do we really design our meshes?**
  - **Are we using the correct discretization?**

Spoiler: Current “fine” meshes seem to converge

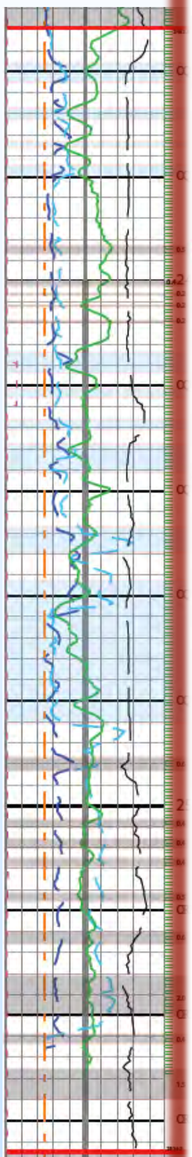
NGHP-02-9 Offshore India Production Test

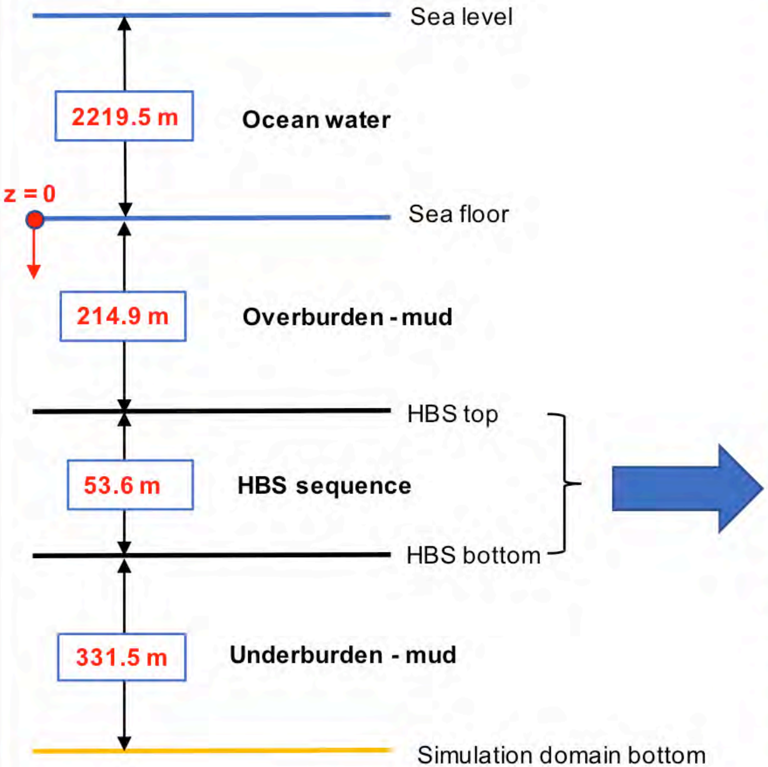


NGHP-02-9 Offshore India Production Test

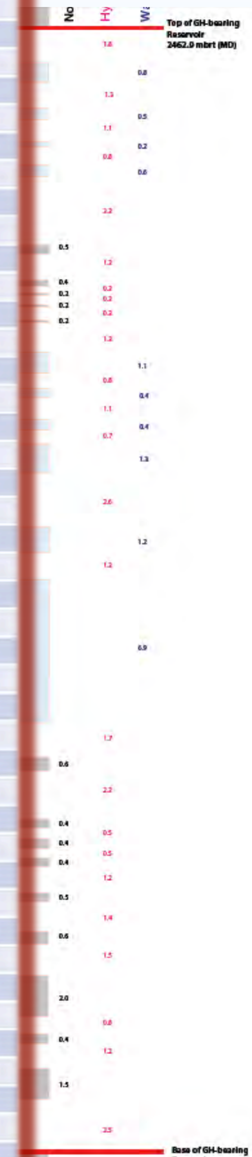


NGHP Test

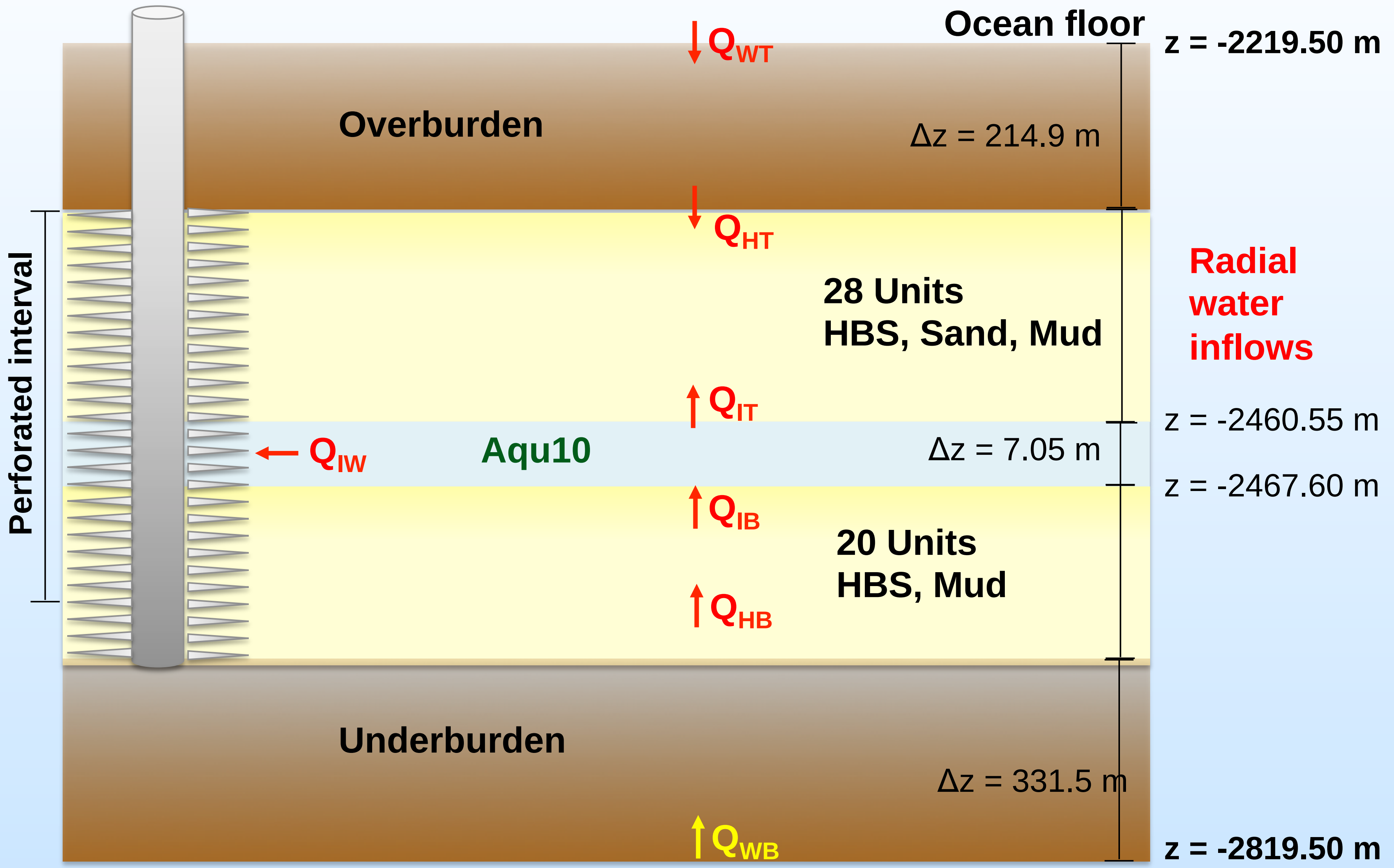




Layer #	Layer Name	Δz (m)	Z_b (m)
1	Hyd01	1.8	-216.7
2	Aqu01	0.8	-217.5
3	Hyd02	1.3	-218.8
4	Aqu02	0.5	-219.3
5	Hyd03	1.1	-220.4
6	Aqu03	0.2	-220.6
7	Hyd04	0.8	-221.4
8	Aqu04	0.6	-222.0
9	Hyd05	3.3	-225.3
10	Mud01	0.5	-225.8
11	Hyd06	1.3	-227.1
12	Mud02	0.4	-227.5
13	Hyd07	0.3	-227.8
14	Mud03	0.2	-228.0
15	Hyd08	0.4	-228.4
16	Mud04	0.2	-228.6
17	Hyd09	0.5	-229.1
18	Mud05	0.2	-229.3
19	Hyd10	1.3	-230.6
20	Aqu05	1.1	-231.7
21	Hyd11	0.8	-232.5
22	Aqu06	0.3	-232.8
23	Hyd12	1.1	-233.9
24	Aqu07	0.4	-234.3
25	Hyd13	0.7	-235.0
26	Aqu08	1.3	-236.3
27	Hyd14	2.6	-238.9
28	Aqu09	1.2	-240.1
28	Hyd15	1.3	-241.4
30	Aqu10	6.9	-248.3
31	Hyd16	1.7	-250.0
32	Mud06	0.6	250.6
33	Hyd17	2.3	-252.9
34	Mud07	0.4	-253.3
35	Hyd18	0.5	-253.8
36	Mud08	0.4	-254.2
37	Hyd19	0.5	-254.7
38	Mud09	0.4	-255.1
39	Hyd20	1.2	-256.3
40	Mud10	0.4	-256.7
41	Hyd21	1.4	-258.1
42	Mud11	0.6	-258.7
43	Hyd22	1.5	-260.2
44	Mud12	2.0	-262.2
45	Hyd23	0.8	-263.0
46	Mud13	0.4	-263.4
47	Hyd24	1.2	-264.6
48	Mud14	1.4	-266.0
49	Hyd25	2.5	-268.5

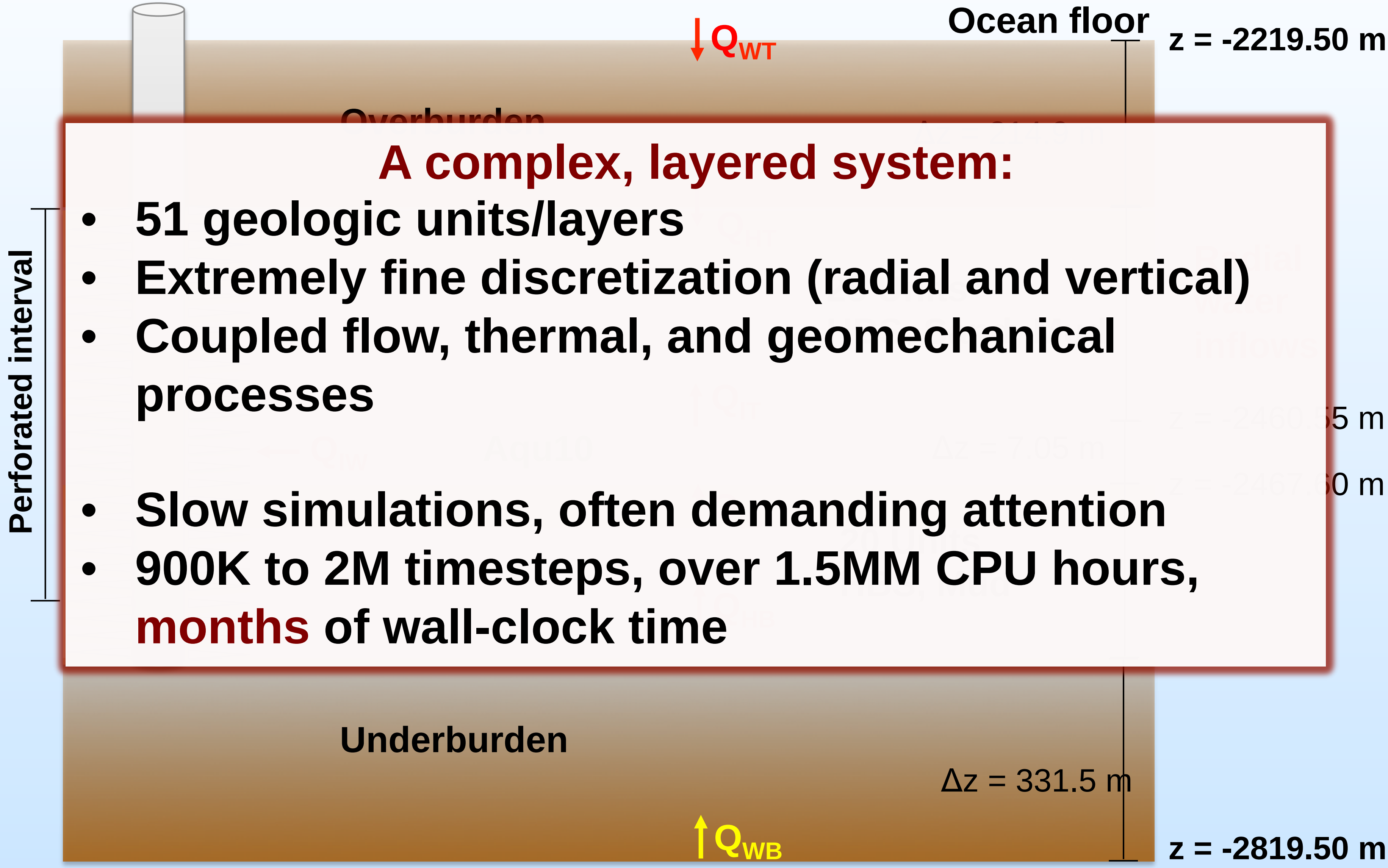


NGHP-02-9 Offshore India Production Test



Discretization: 452 x 525 in (r,z) – 237K elements, 948K eqs

NGHP-02-9 Offshore India Production Test



A complex, layered system:

- **51 geologic units/layers**
- **Extremely fine discretization (radial and vertical)**
- **Coupled flow, thermal, and geomechanical processes**

- **Slow simulations, often demanding attention**
- **900K to 2M timesteps, over 1.5MM CPU hours, months of wall-clock time**

Discretization: 452 x 525 in (r,z) – 237K elements, 948K eqs

NGHP-02-9 Offshore India Production Test

Flow & Thermal Properties:

- 51 separate units
- 25 Hydrate Layers, 10 sand layers: Φ = 0.45, **$k_r = k_0$ = 10 D**
- k_{eff} = 1.0 mD when S_H = 0.75, $k_{rel} = (S^*)^n$ = 0.001, n = 3.86
- 10 mud Interlayers: Φ = 0.45, k_r = 0.01 mD, $k_z = k_r$
- Overburden & Underburden: Same as mud layers
- Thermal properties (all): κ_Q (W/m/s) = 0.3 dry, 1.76 wet

Initial conditions:

- Pressure: Hydrostatic distribution
- Temperature: Distribution by equation provided by USGS (Collett)
- Hydrate saturations: 0.75 in all HBS

Production Method: constant bottomhole *P* = 3 MPa

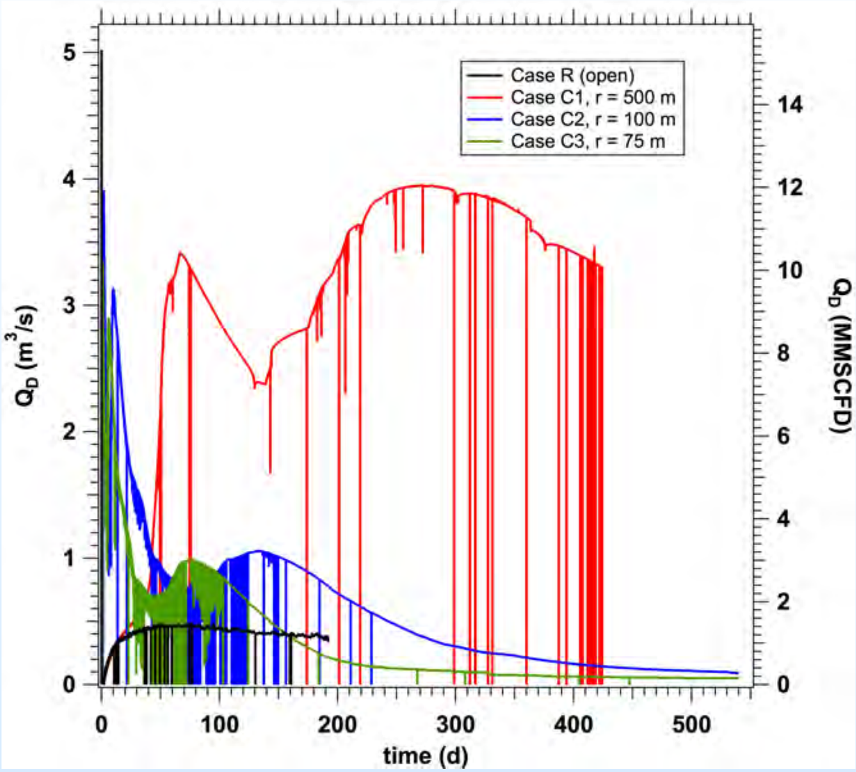
Boundaries:

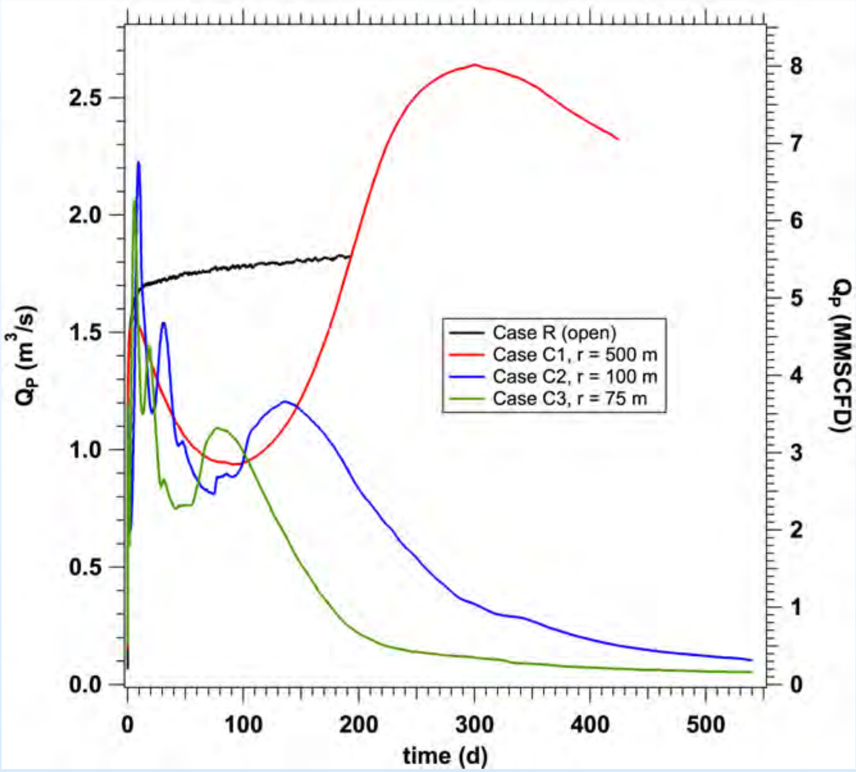
- Top: Ocean Floor, Constant *P, T*
- Bottom: @ -2788 m, Constant *P, T*
- Lateral: @ r = 2000 m, Constant *P, T*

Production Strategies:

- **(up to) 540 day field test**
- **Single well**
- **Multiple wells (pattern), *r* = 500 m, 100 m, 75 m**

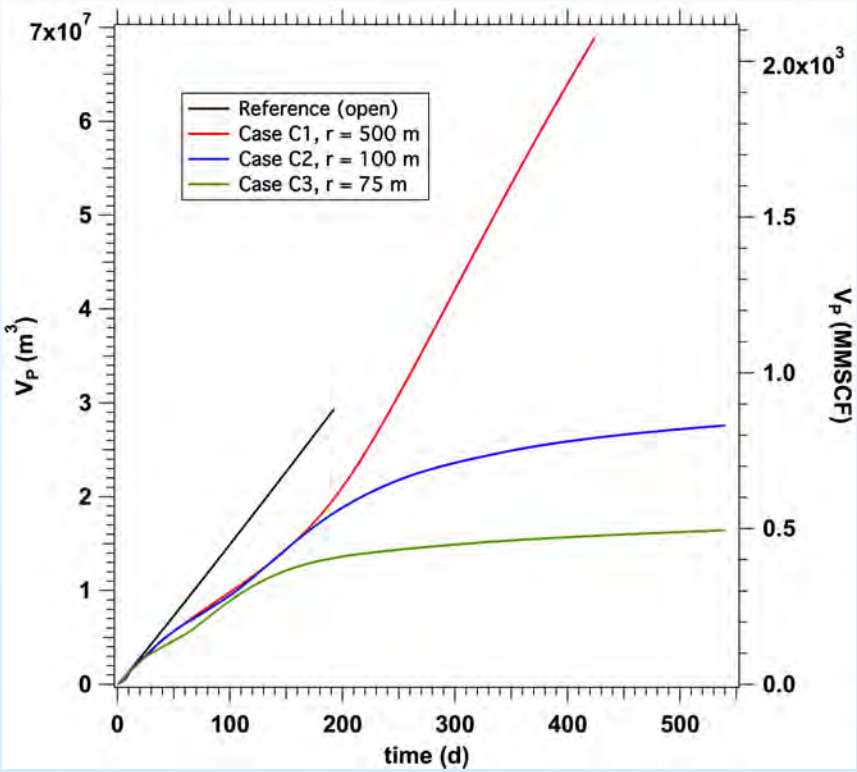
NGHP-02-9 Offshore India Production Test

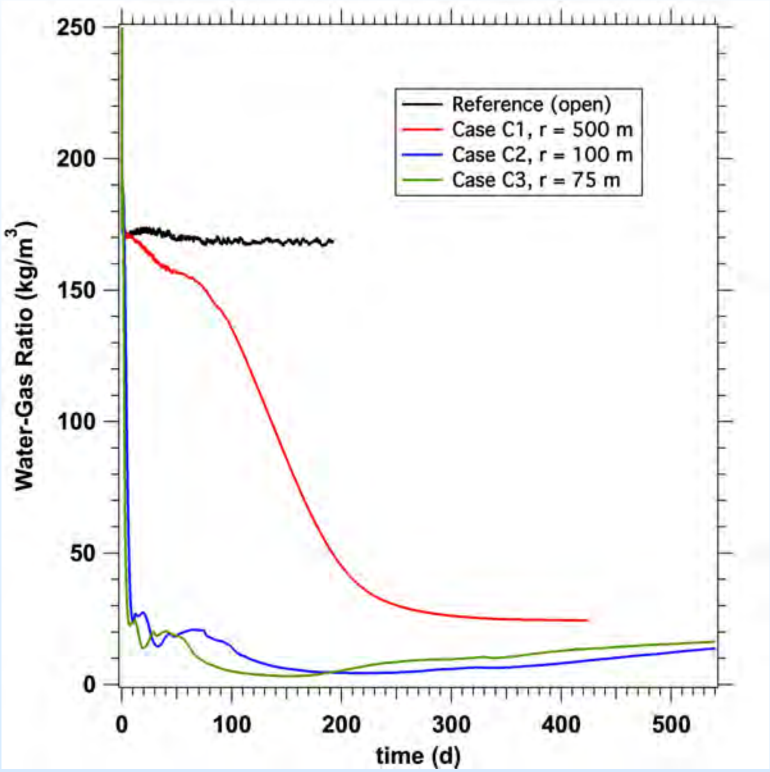




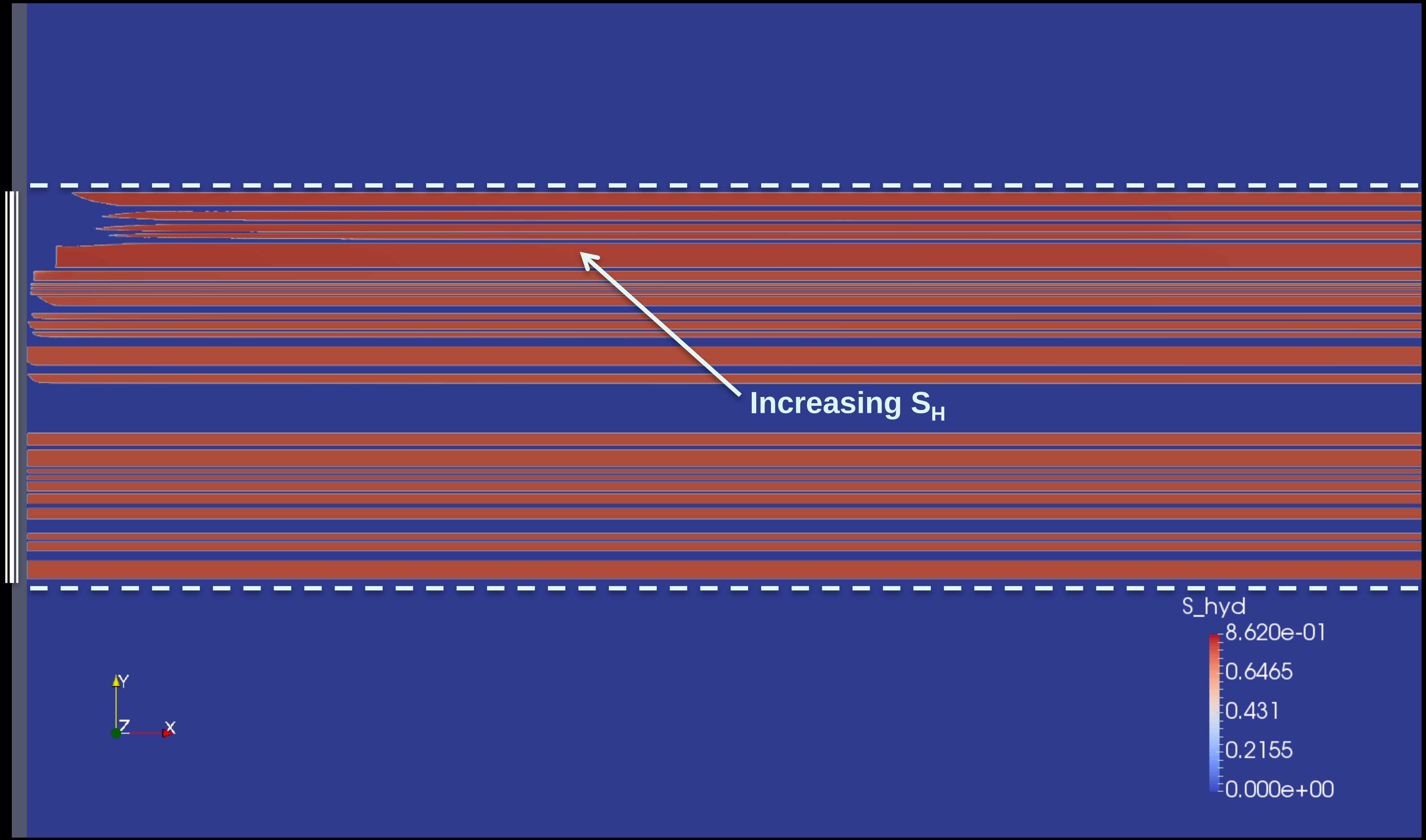
- Reference case (single well, open) abandoned at quasi-steady state
- Multiple wells, but not too tight, enhance gas generation and production

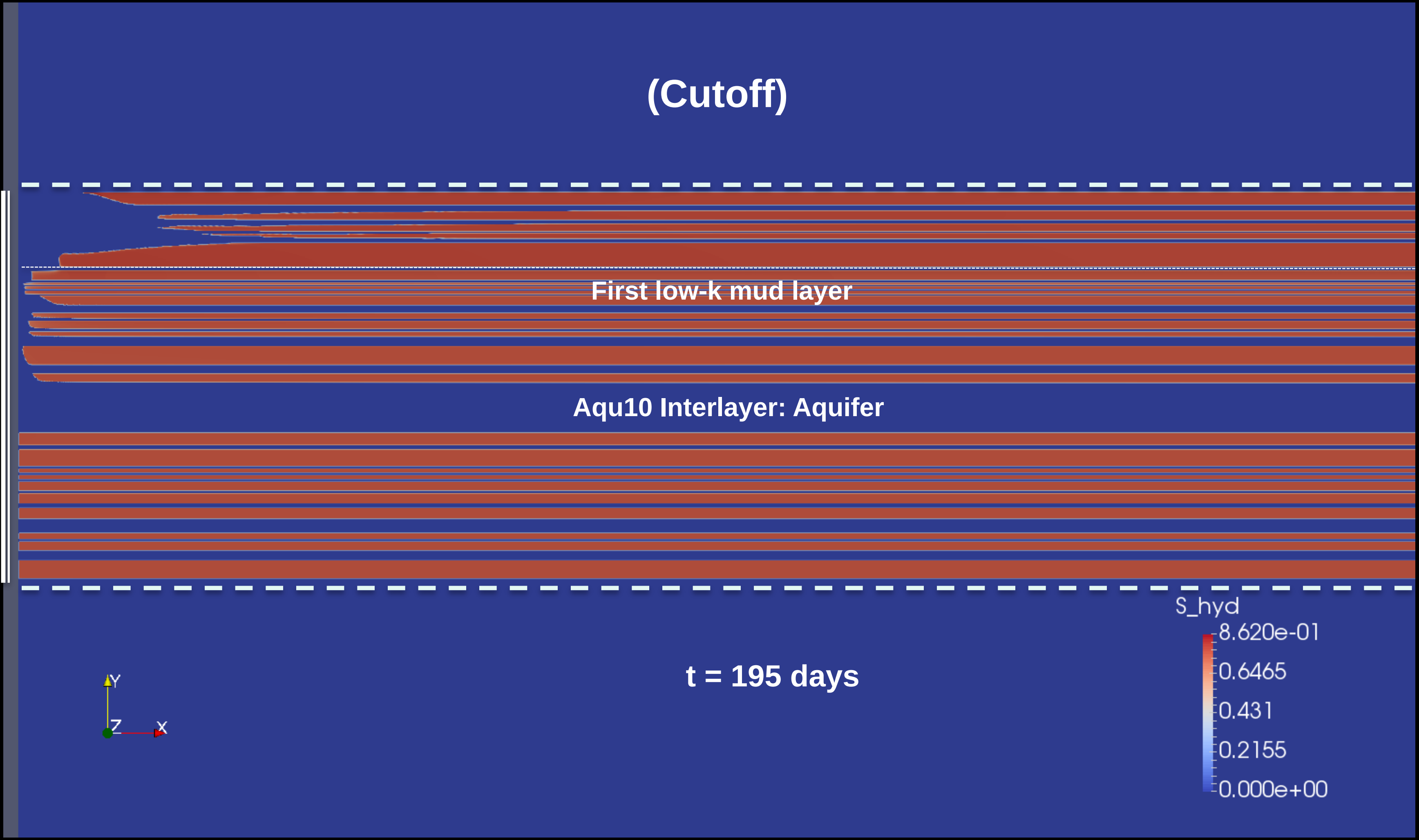
NGHP-02-9 Offshore India Production Test

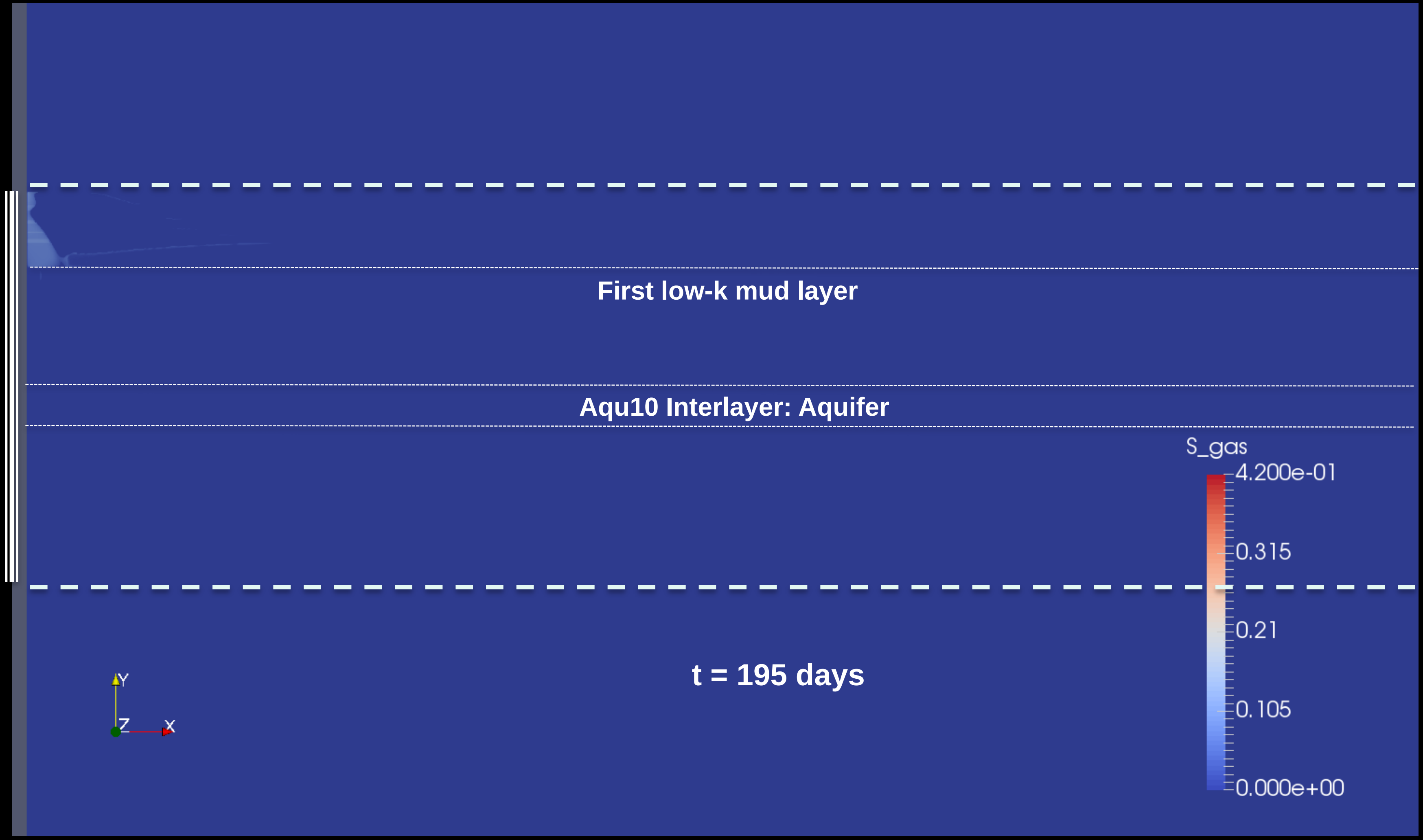


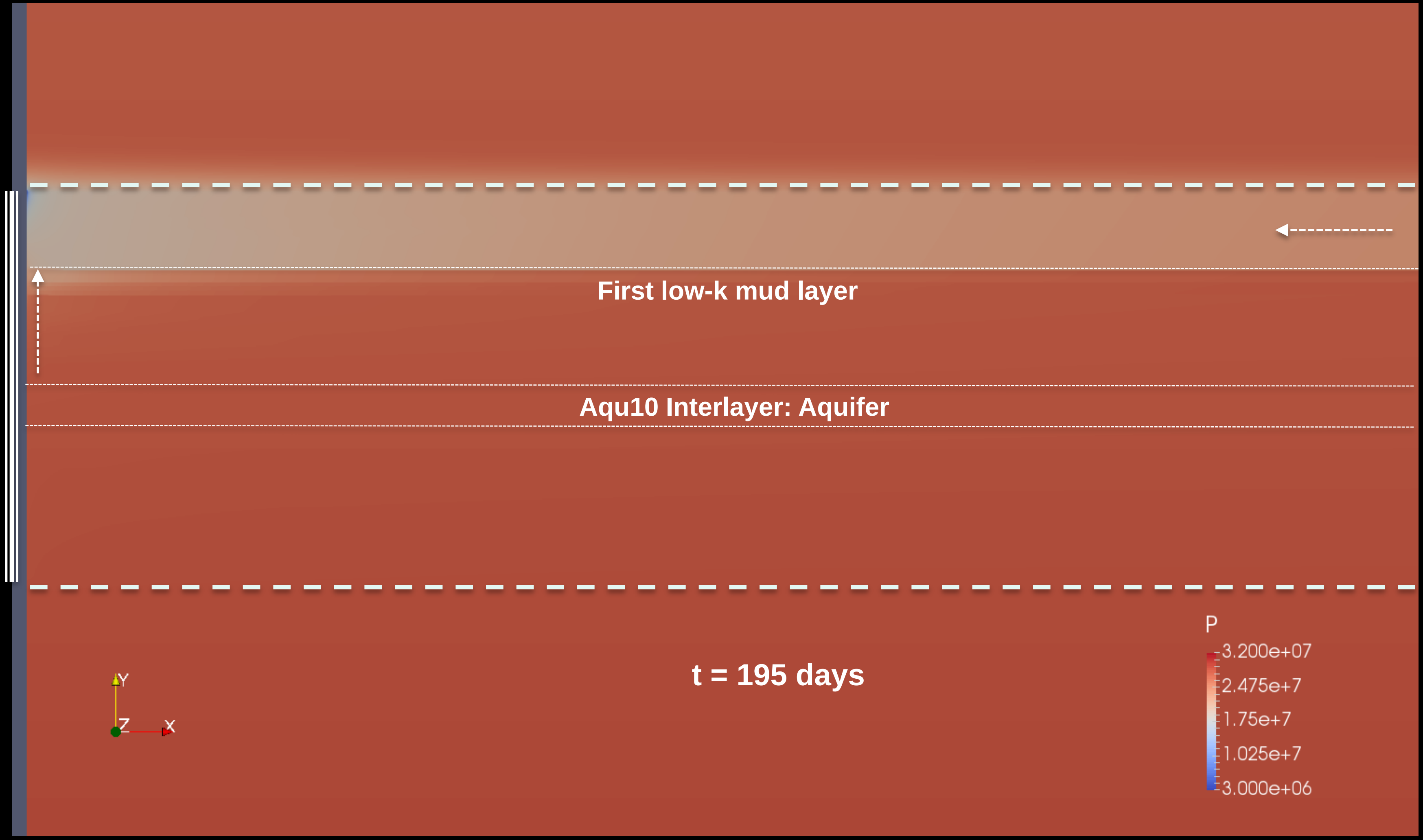


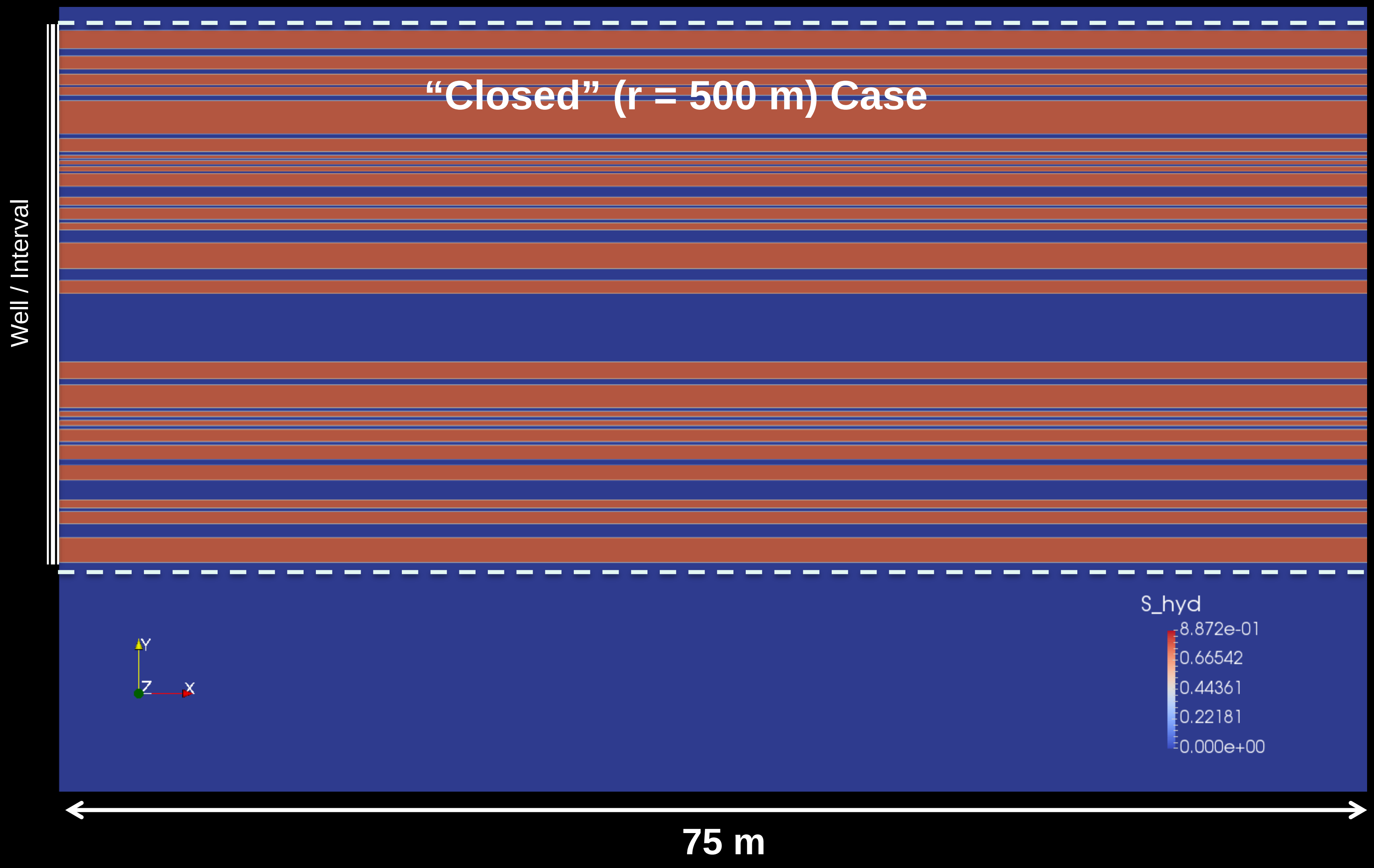
- Reference case (single well, open) abandoned at quasi-steady state
- Multiple wells, but not too tight, enhance gas generation and production
- High volumes of gas can be produced…
- …with a lot of water.

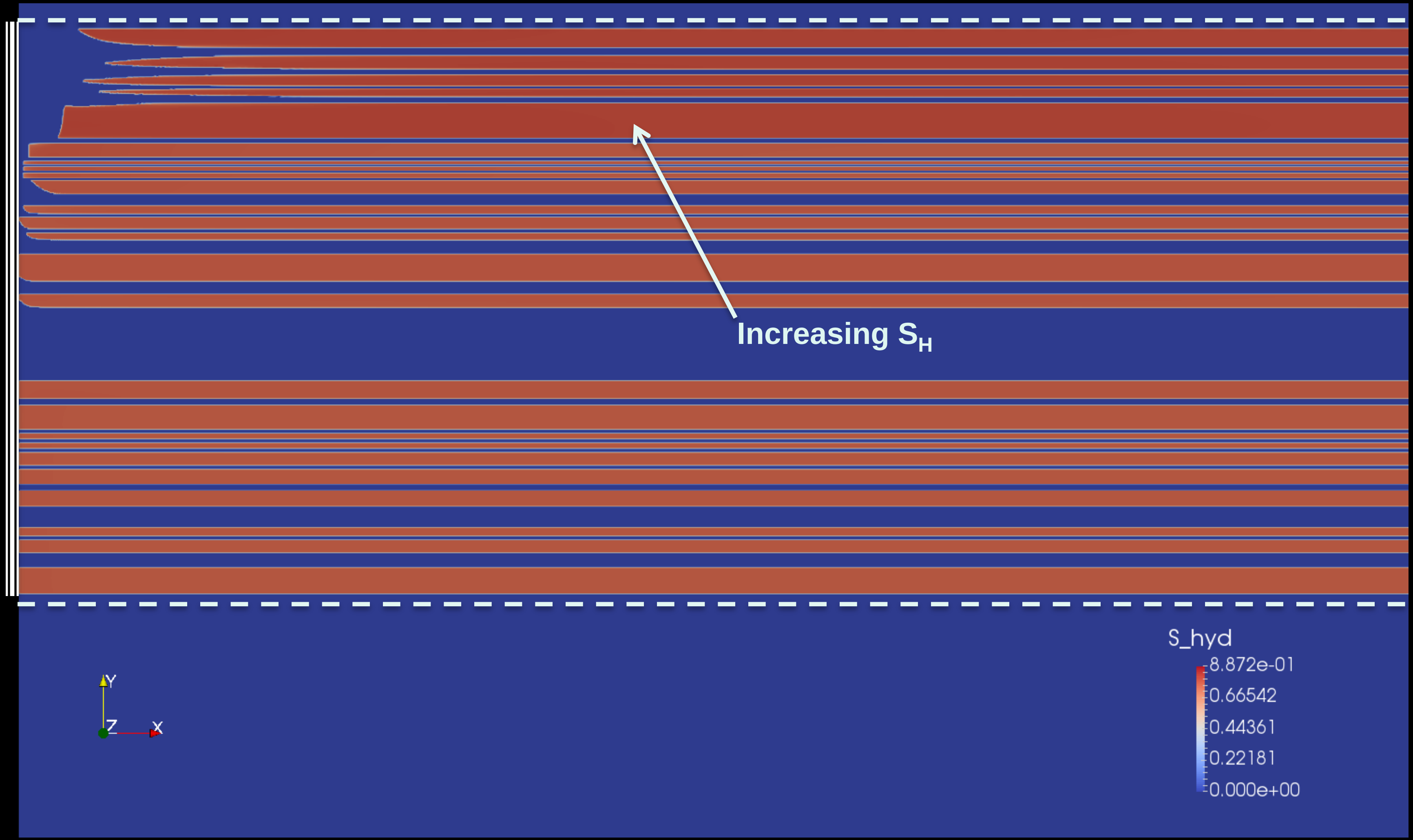

Increasing S_H
S_hyd
8.620e-01
0.6465
0.431
0.2155
0.000e+00
Y
Z
X


(Cutoff)
First low-k mud layer
Aqu10 Interlayer: Aquifer
t = 195 days
S_hyd
8.620e-01
0.6465
0.431
0.2155
0.000e+00
Y
Z
X

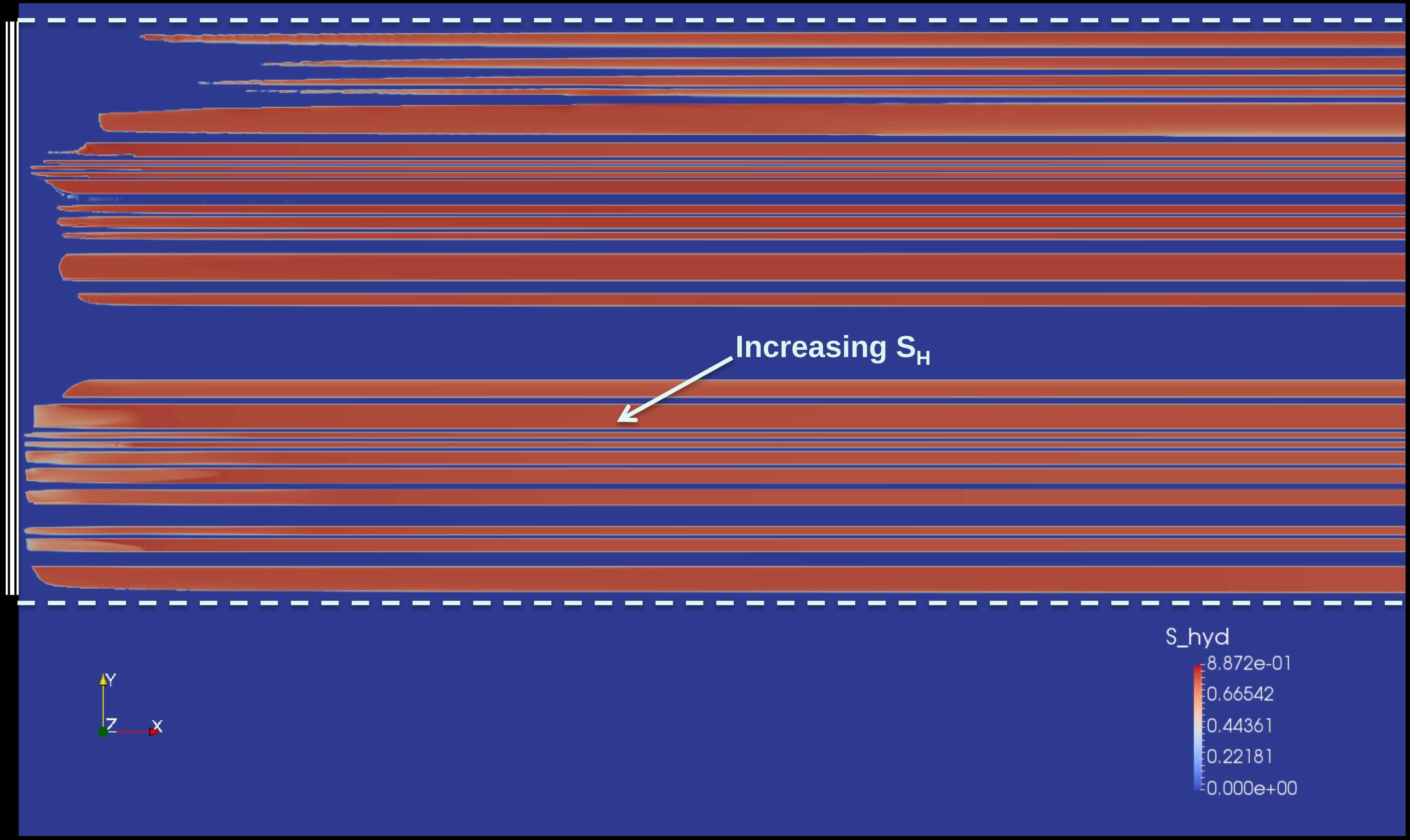

First low-k mud layer
Aqu10 Interlayer: Aquifer
S_gas
4.200e-01
0.315
0.21
0.105
0.000e+00
t = 195 days
Y
Z
X


First low-k mud layer
Aqu10 Interlayer: Aquifer
t = 195 days
P
3.200e+07
2.475e+7
1.75e+7
1.025e+7
3.000e+06
Y
Z
X

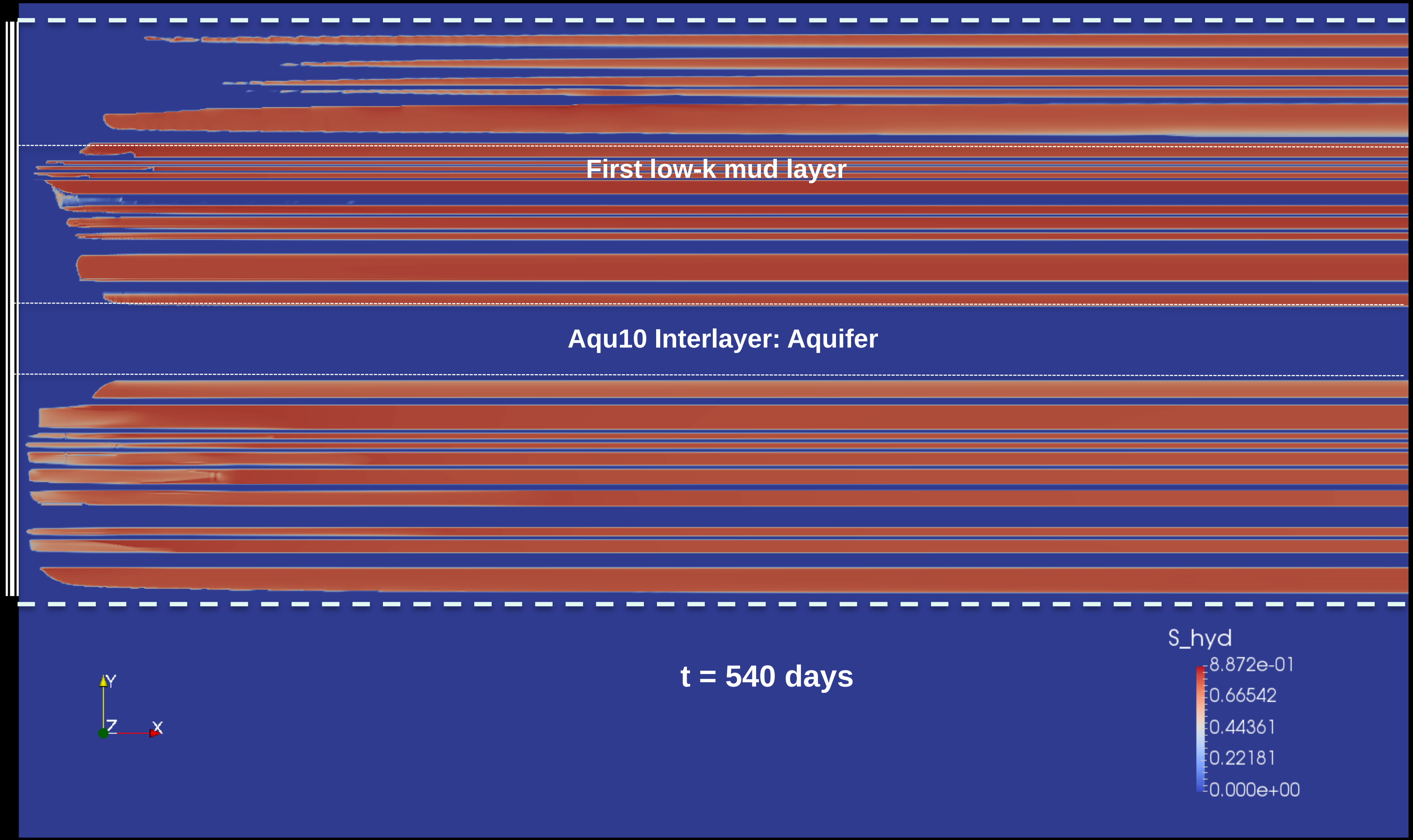

"Closed" (r = 500 m) Case
Well / Interval
S_hyd
8.872e-01
0.66542
0.44361
0.22181
0.000e+00
Y
Z
X
75 m



Increasing S_H
S_hyd
8.872e-01
0.66542
0.44361
0.22181
0.000e+00
Y
Z
X

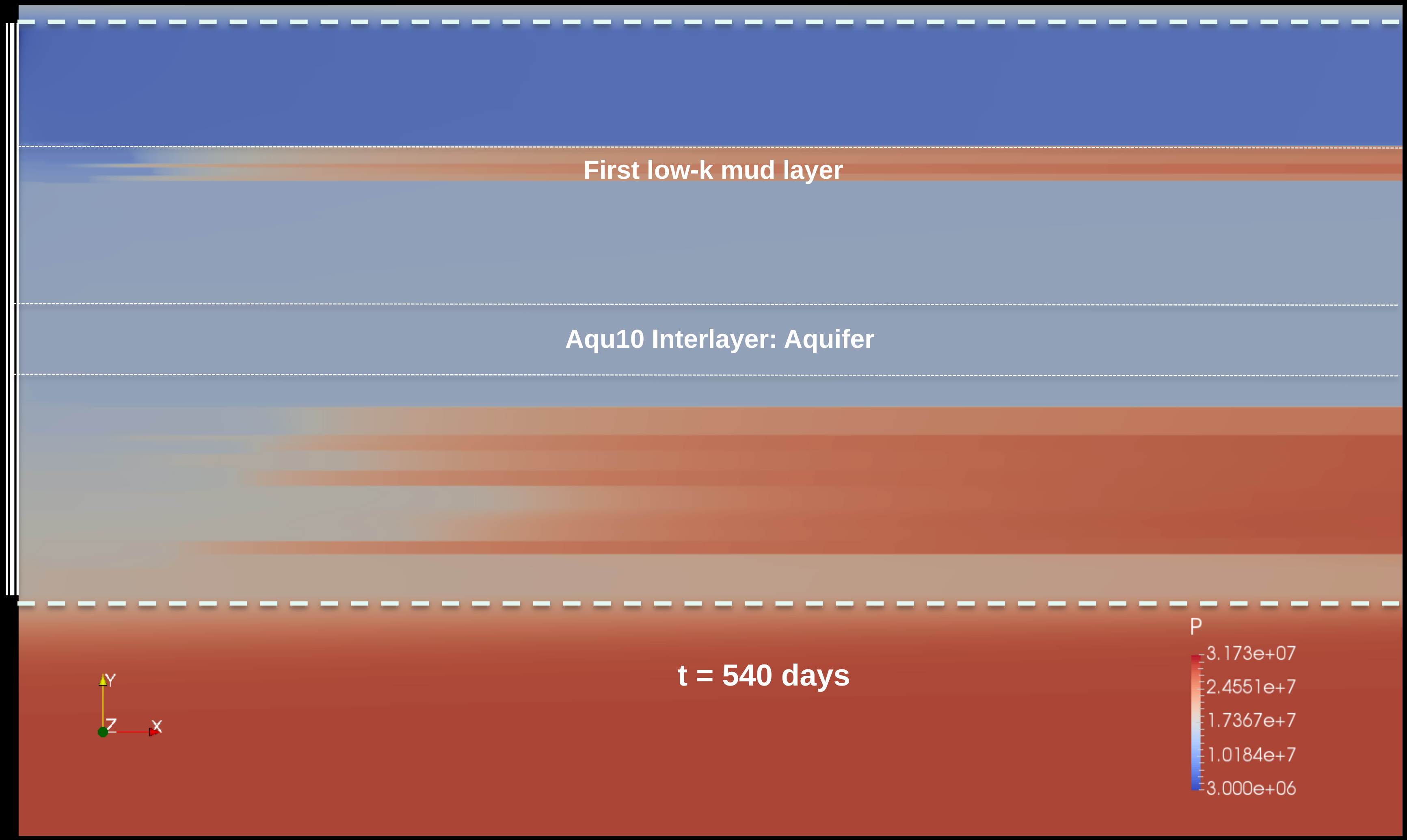


Increasing S_H
S_hyd
8.872e-01
0.66542
0.44361
0.22181
0.000e+00
Y
Z
X



First low-k mud layer
Aqu10 Interlayer: Aquifer
t = 540 days
S_hyd
8.872e-01
0.66542
0.44361
0.22181
0.000e+00
Y
Z
X


First low-k mud layer
Aqu10 Interlayer: Aquifer
t = 540 days
S_gas
4.384e-01
0.3288
0.2192
0.1096
0.000e+00
Y
Z
X



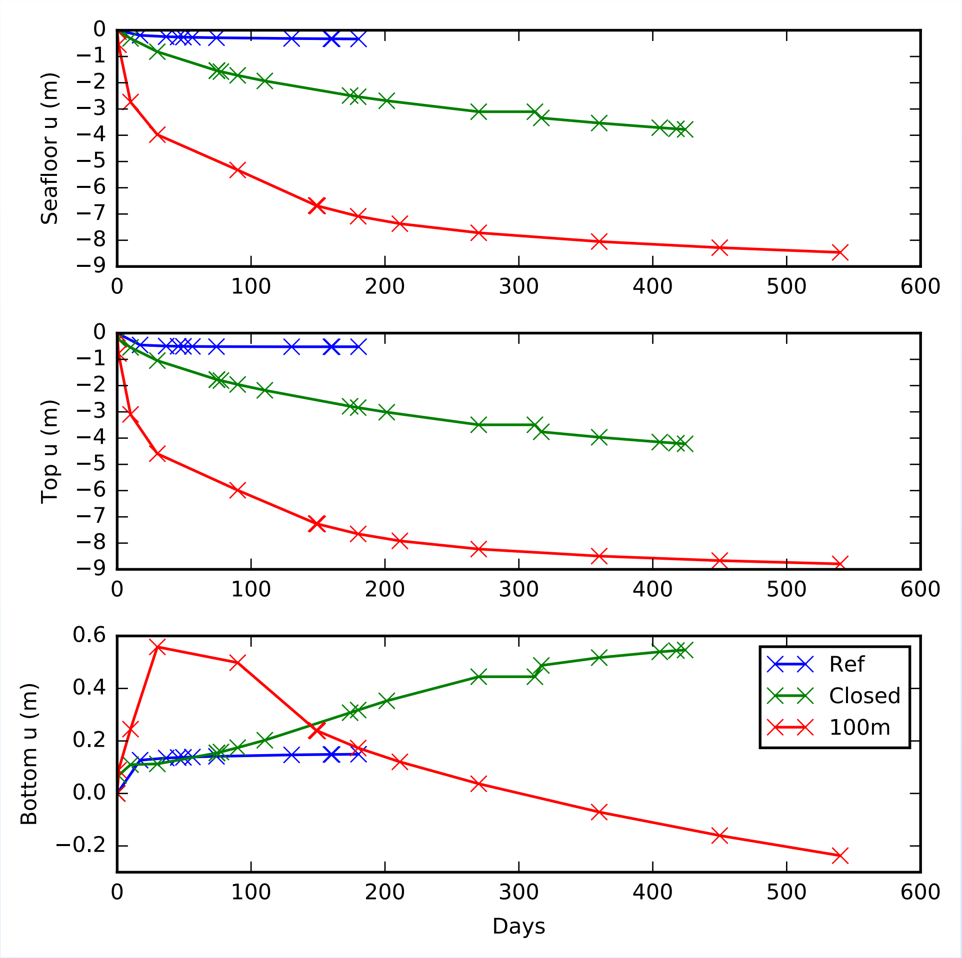
First low-k mud layer
Aqu10 Interlayer: Aquifer
t = 540 days
P
3.173e+07
2.4551e+7
1.7367e+7
1.0184e+7
3.000e+06
Y
Z
X

NGHP-02-9 Offshore India Production Test

Geomechanical Response

- **Forward-coupling of T+H to "Millstone" simulator**
- **Saves millions of CPU-hours**
- **Demonstrates ability to post-process results to estimate geomechanical response**

- **Subsidence/uplift significant but reasonable**



NGHP-02-9 Offshore India Production Test

NGHP-02-9 site does not appear to be a good candidate for a field test*

*Assuming reservoir parameters/simulation inputs are correct

Production case: appears quite promising, but:

- **Water control issues (Aqu10 unit)**
- **Very case-specific behavior**
- **Geomechanics must be considered**

- **Significant data gaps: better data needed for reliable simulations**
- **Careful study of the site and a long term production test a must**

Moridis, G.J., Reagan, M.T., Queiruga, A.F., Collett, T.S., Boswell, R., Evaluation of the Performance of the Oceanic Hydrate Accumulation at the NGHP-02-9 Site of the Krishna-Godawari Basin During a Production Test and Under Full Production, submitted to *J. Marine and Petroleum Geology*.

Moridis, G.M., Reagan, M.T., Queiruga, A.F., Geomechanical Stability and Overall System Behavior of Sloping Oceanic Accumulations of Hydrates Responding to Dissociation Stimuli, OTC-24896-MS, *Proc*. Offshore Technology Conference-Asia, 20 March 2018.

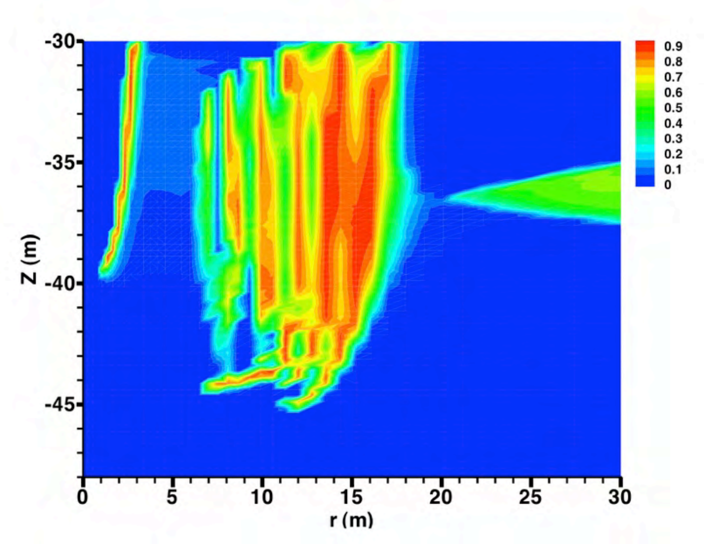
Accomplishments to Date

TOUGH+HYDRATE and pTOUGH+HYDRATE are used:

- by **40+** research organizations in 18 countries
- by **8** international oil and gas companies

LBNL and/or T+H have been involved in the planning and design of *nearly* every international field test or proposed field test:

- **Mallik (DOE/Japan)**
- **PBU-L106 (DOE)**
- **"Mt. Elbert" Unit-D (DOE)**
- **Ignik Sikumi (DOE/ConocoPhillips)**
- **AC818/"Tigershark" (DOE/Chevron)**
- **Ulleung Basin (DOE/KIGAM)**
- **India NGHP-02 (DOE/India)**
- **Shenhu (China)** (T+H code)



Accomplishments to Date

Other activities:

- **Nearly 20 years of experience in laboratory and simulation work**
- **Over 110 publications (50+ peer-reviewed, 60 reports and conference papers)**
- **Over 70+ national and international presentations (many invited)**
- **9 keynote presentations**
- **Invited presentations at the 2010, 2012, 2018 Gordon Research Conferences (2018 Keynote)**
- **Feature articles in Journal of Petroleum Technology, Oil and Gas Reporter, Nature Reports Climate Change**

- **Regular training courses (national and international)**
- **2 MSc and 3 PhD students**

Lessons Learned

Long-term experience tells us:

- Complex hydrate systems are challenging to simulate!
  - Fine meshes: discretization determines evolution!
  - Sharp fronts → small timesteps
  - **Consumption of CPU-hours: 10^6++**
- Practical production targets must have good boundaries
- Simulations constrained by data limitations
  - **Are we capturing enough heterogeneity?**
  - Are the meshes fine enough? (CCS)
- Geomechanical response critical to evaluating potential

Paths Forward

Next budget period:

1. Support of the Design of the Proposed Alaska Field Test
   - Model development, scoping runs
   - Production simulation, sensitivity studies
2. Participation in the (ongoing) Code Comparison Study (IGHCCS2)
3. Support of DOE's International Activities and Collaborations
   - India NGHP
   - KIGAM
4. **Investigation of Machine Learning Methods for Reduced Order Modeling**
5. Code Maintenance, Upgrades, and Support
6. Publications, Travel, Tech Transfer

Synergy Opportunities

- The **2nd Code Comparison Study** is identifying the most critical issues related to simulator design and simulation techniques
- **Comparisons of results** obtained using the various approaches builds confidence in the results and the program
- The large scale of hydrate development requires international collaboration

Appendix

Benefit to the Program

The objectives of the Program are to:

- Identify and accelerate development of economically-viable technologies to more effectively locate, characterize, and produce natural gas and oil resources, in an environmentally acceptable manner
- Characterize emerging oil and natural gas accumulations at the resource and reservoir level and publish this information in a manner that supports effective development
- Catalyze the development and demonstration of new technologies and methodologies for limiting the environmental impacts of unconventional oil and natural gas development activities

Benefit to the Program

Benefits to the program include:

- Developing the necessary knowledge base and quantitative predictive capability for the description of the most important processes and phenomena associated with gas production from hydrate deposits
- Developing the fastest and most advanced numerical simulation capabilities for the solution of the difficult problems of stability, characterization, and gas recovery from methane hydrate deposits
- Involvement in the planning and design of nearly every US and international field test of hydrate technologies

Project Overview

Goals and Objectives

The overall objective of this effort is to further enhance earlier-developed powerful numerical simulators, and

- Use them to perform studies on the characterization and analysis of recoverable resources from gas hydrate deposits,
- Evaluate of appropriate production strategies for both permafrost and marine environments,
- Analyze the geomechanical behavior of hydrate-bearing sediments,
- Provide support for DOE's hydrate-related activities and collaborative projects

The research will support the hydrate scientific community by making available the fastest and most advanced numerical simulation capabilities for the solution of the difficult problems of stability, characterization, and gas recovery from methane hydrate deposits.

Organization Chart

George Moridis, PI

Reservoir Modeling

George Moridis, Matthew Reagan, Alejandro Queiruga

Gantt Chart

Budget Period	#6, FY 17		#6, FY18			
Quarter	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Task 1.0 Project Management and Planning						
Task 2.0 Code Maintenance & Upgrades						
Subtask 2.6: Geomechanical Coupling of STONE/T+H						**X**
Task 3.0 Support of DOE's Field Activities and Collaborations						
Subtask 3.6: Detailed Analysis of the Production Potential of Hydrates Deposits Offshore India						**X**
Subtask 3.7: Participation in the Code Comparison Study of Coupled Flow, Thermal and Geomechanical Processes						**X**
Task 4.0 Assessment of Resource Recoverability From Natural Hydrate Deposits						
Subtask 4.4: Production Strategies to Avoid Dissociation Constraints During Production from Oceanic Hydrate Deposits						**X**
Task 5.0 Support for the Design and Analysis of Laboratory Experiments						

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